e^+e^- pairs: a clock and a thermometer of heavy ion collisions

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Abstract. Recently, there is growing evidence that a new state of matter is formed in $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions at RHIC: a strongly coupled Quark Gluon Plasma of partonic degrees of freedom which develops a collective motion. Dileptons are not affected by the strong interaction and can therefore probe the whole time evolution of the collision. Thus they may be sensitive to the onset of deconfinement, chiral symmetry restoration, as well as the production of thermal photons via their internal conversion. The PHENIX experiment measured the production of e^+e^- pairs in p+p and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. An enhanced dilepton yield in the mass range 150< m_{ee} <750 MeV/c^2 was measured. The excess increases faster with centrality than the number of participating nucleons and is concentrated at p_T <1GeV/c. At higher p_T the excess below 300 MeV/c^2 in mass has been related to an enhanced production of direct photons, possibly of thermal origin.

1. The role of dileptons and photons in heavy ion collisions

One of the main goals in nuclear physics is to investigate QCD and its properties under extreme conditions of hot and dense matter, experimentally realized in relativistic heavy ion collisions. The energy density reached in those collisions by far exceeds typical hadronic values and fundamental constituents of matter, quarks and gluons, are no longer confined to color neutral hadrons. Lattice QCD calculations indicate that this significant change in the structure of matter coincides with the restoration of chiral symmetry, which is linked to the origin of the hadron masses [1]. Experimental results from the Relativistic Heavy Ion Collider (RHIC) have established the formation of a Quark Gluon Plasma in Au+Au collisions at $\sqrt{s_{NN}}$=200GeV [2]. A large set of data allows to characterize the nature of the medium created. It has very high density, as indicated by the large energy loss of light and heavy quarks, and thermalizes rapidly, as indicated by the significant elliptic flow of these partons. Many open questions remain, for example: what is the temperatures, the corresponding system sizes of the matter at the early stages, and the temperature evolution of the system from the formation time to thermal freeze-out? Is chiral symmetry restored? While signatures of chiral symmetry restoration manifest themselves in non-observable order-parameters (such as the quark condensate), links can be established with the hadronic excitations and modifications of their fundamental properties, such as mass, width and life-time.

Electromagnetic probes, such as real and virtual photons (i.e. dileptons), provide key measurements to address these open questions. Created through the entire space-time evolution of the system, they escape, once emitted, from the strongly-interacting medium without final-state interaction. The measurement of direct thermal radiation (photons or dileptons) can be used to derive a limit on the initial temperature of the QGP created in heavy ion collisions at RHIC. Hydrodynamical models can predict the slope of the thermal photon spectrum with thermodynamical parameters which describe the initial energy density ϵ_0 in terms of temperature T_0 and time τ_0. In the hadronic phase dilepton production is mediated by light vector mesons. The ρ (770) meson, because of its small life time (1.3 fm/c) and the strong coupling to the $\pi - \pi$ channel is a very suitable probe to test predicted in-medium modifications. The p_T of dileptons carry information about key properties of the fireball, such as the temperature and the flow. Since they are emitted during the full time evolution, they get small flow and high temperature at early times, and increasingly larger flow and smaller temperatures at later times, unlike hadrons whose flow arises when they decouple from the medium. The interpretation of dilepton speactra may then result in a *clock* and a *thermometer* of heavy ion collisions.

2. Review the results from the pre-RHIC era

Dileptons and photons have already received attention in the SPS program. An enhanced dilepton yield in the low mass region (LMR: $m < 1$GeV) with respect to the sum of known hadronic sources was first reported by CERES [3] and HELIOS [4] in S+Au and S+W reactions at 200 AGeV. The discovery triggered numerous theoretical interpretations [5] which concentrated on the role of $\pi - \pi$ annihilation $\pi^+\pi^- \leftrightarrow \rho \rightarrow e^+e^-$. Theoretical approaches based on in-vacuum properties of the ρ systematically failed to described the data. More successful was theoretical work with medium-modified spectral functions, including scenarios where the mass of the ρ meson *drops*, according to the Brown-Rho scaling conjecture, or *broadens* by strongly interacting with the hot and dense medium. The CERES data also show that such enhancement rises significantly steeper than linear with charged particle density and is concentrated at very low pair-p_T , consistent with the interpretation that the excess is due to binary annihilation processes [6]. NA60 recently confirmed the excess of pairs in In+In collisions at 158 AGeV [7] and analyzed the slope parameter T_{eff} extracted from the corresponding pair-p_T spectra which rises with dilepton mass consistent with the expectations of radial flow of the hadronic decay source [8, 9]. Several recent theoretical works reasonably reproduce features like the mass distribution of the enhancement, the centrality dependence, and the radial flow of the source. However the pair-p_T spectra exhibit a steep rise towards its lower values that has not been explained by any model so far [10].

An excess of dilepton pairs has also been observed by NA38/NA50 [11] in the intermediate mass region (IMR: $1 < m < 3$ GeV), where the sensitivity to thermal radiation increases. NA60 data suggest that this enhancement can not be attributed to decays of D-mesons but may result from prompt production, as expected for thermal radiation. The sudden drop of the slope parameter T_{eff} above 1 GeV/c^2 in mass, advocates a partonic (i.e. non-flowing) origin of this direct radiation [12, 8, 9]. While similar kinematic window, $q_T = \sqrt{m^2 + p_T^2} = 2$ GeV, was addressed by WA98 [13] to measure direct photon spectra, the two points at low-p_T ($Q_T < 0.4GeV$) extracted via HBT methods are enhanced with respect to the sum of hadron gas, QGP radiation and pQcd calculations. They challenged the existing predictions which could reconcile with the data only after the inclusion of soft Bremsstrahlung [14] off $\pi\pi$ and πK from the late stages of the fireball.

3. The new results at RHIC

The PHENIX experiment at RHIC extends dileptons and photon measurements with the analysis of p+p and Au+Au collisions in a new energy regime of $\sqrt{s_{NN}}$=200 GeV. Thanks to its versatility in particle identification, high granularity and high rate capability, PHENIX can measure electrons and photons with high precision at mid rapidity and muons at forward rapidity. Detailed descriptions of the electron pair analyses can be found in [15, 16, 17]. The pair-signal is compared to a cocktail of hadronic sources, semi-leptonic decays of heavy quarks and Drell-Yan. In p+p collisions PHENIX has measured the spectra of pions [19, 20], kaons [20], η [21], ω [22], ϕ [23], J/ψ [24] via several decay channels, see Figure 1. Pions are fitted with a modified Hagedorn function; the other data are fitted with the same function scaled with m_T and a free normalization factor. Excellent agreement with the data is achieved. Figure 2 shows the e^+e^- pair yield as a function of pair mass for p+p (left) and Au+Au (right) both compared to an absolutely normalized cocktail tuned for the respective collision system. The contribution from heavy quark decays has been fitted to the p+p data using the e^+e^- pair distribution predicted by PYTHIA [25]. The charm cross section was found to be $\sigma_{c\bar{c}}$ =544±39(stat)±142(syst) ±200(model) μb consistent with QCD calculations and with more precise measurements from single leptons (567 ±57±193 μbarn [18]). This latter was used for the Au+Au cocktail, scaled by the average number of binary collisions (258±25) [26]. The p+p data agree very well with the sum of all known sources.

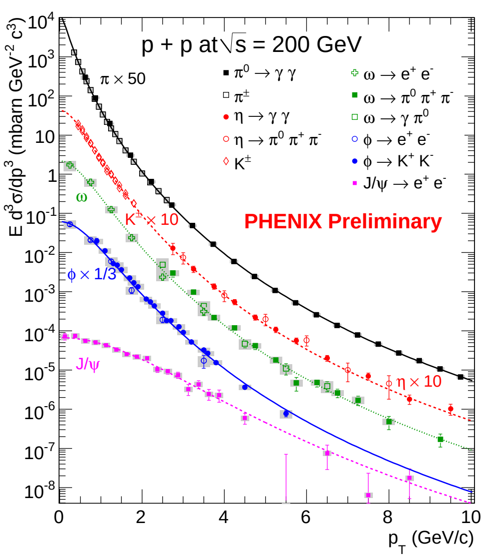

Figure 1. Compilation of meson production cross sections in p+p collisions at $\sqrt{s}$=200 GeV. Shown are data for neutral [19] and charged pions [20], η [21], Kaons [20], ω [22], ϕ [23] and J/ψ [24] compared to the m_T scaling parameterization.

In Au+Au the data below 150 MeV/c^2 are well described by the cocktail of hadronic sources. The vector mesons ω, ϕ and J/ψ are reproduced within the uncertainties. However, in the mass region from 150 to 750 MeV/c^2, the yield is enhanced above the expectations by a factor of 3.4±0.2(stat)±1.3(syst)±0.7(model), where the first error is the statistical error, the second the systematic uncertainty of the data, and the last error is an estimate of the uncertainty of the expected yield from the cocktail. Above the ϕ meson mass the data seem to be well described by the continuum calculation based on PYTHIA. However the observation of a strong

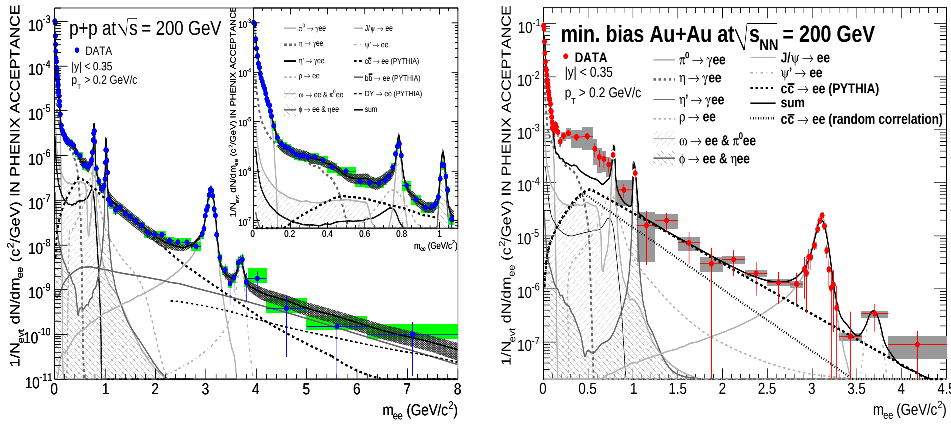

Figure 2. Electron-positron pair yield per inelastic collision as function of pair mass in p+p (left [16]) and Au+Au (right [15]). The data are compared to a cocktail of known sources. The inset in p+p shows the same data but focuses on the low mass region.

suppression and a large v_2 of single electrons from heavy quark decays suggest that charm might be thermalized [27]. This may correspond to a loss of the dynamical correlation of c and $\bar{c}$ quarks indicated by the second charm curve (Fig.2 right), which leads to a much softer mass spectrum and would leave room for significant other contributions, e.g. thermal radiation.

3.1. *The centrality dependence*

To shed more light on the possible origin of the Au+Au enhancement, the centrality and the p_T dependence of the continuum yield are studied. Using simulations based on a Glauber model calculation [28] the average number of participants N_{part} and binary collisions N_{coll} associated with each centrality bin is determined. The centrality bins cover 0-10%, 10-20%, 20-40%. 40-60%, 60-92% fraction of the inelastic Au+Au cross section.

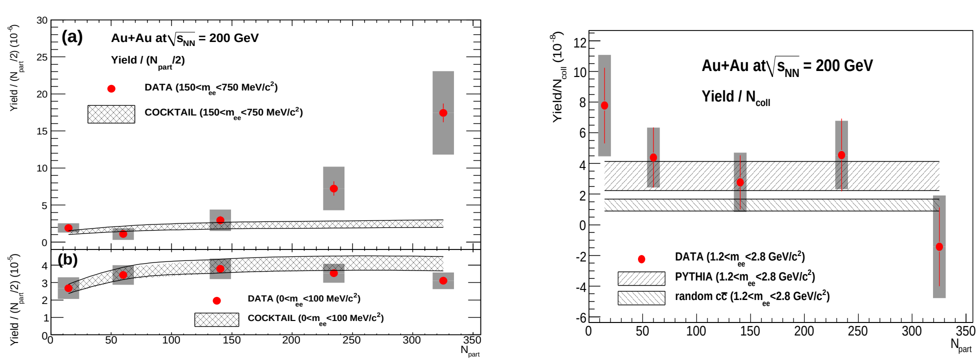

Figure 3. Dielectron yield per participating nucleon pairs $N_{\rm part}/2$ (left) or per binary collisions $N_{\rm coll}$ (right) as function of N_{part} for three different mass ranges compared to the expected yield from the hadron decay model [15].

Fig. 3 (left) shows the centrality dependence of the LMR yield divided by the number of participating nucleon pairs ($N_{\rm part}/2$). While the yield below 100 MeV/c^2, which is dominated by low p_T pion decays, agrees with the expectation from the hadron cocktail, the yield in 150–750 MeV/c^2 rises significantly compared to the expectation, qualitatively consistent with the conjecture that an in-medium enhancement of the dielectron continuum yield arises from scattering processes like $\pi\pi$ or $q\bar{q}$ annihilation.

The yield in the mass region 1.2 to 2.8 GeV/c^2 normalized to the number of binary collisions (Fig. 3 right) shows no significant centrality dependence and is consistent with the expectation based on PYTHIA. However the scaling with N_{coll}, expected for charmed meson decays [27], may be a mere coincidence resulting from two balancing effects: the suppression of charm which increases with N_{part} and a thermal contribution could increase faster than linearly with N_{part}. Such a coincidence may have been observed at the SPS [11], where a prompt component has now been suggested by NA60 [12].

3.2. The $p_{\rm T}$ dependence

Figure 4 compares e$^+$e$^-$ pair invariant mass spectra measured in p+p and in Au+Au collisions to the corresponding expectations from the cocktail of hadron decays and open charm, in different ranges of p_T . The p+p, the Au+Au data and the cocktail are normalized relative to each other in m < 30 MeV/c^2. The p+p data is consistent with the expectations from the cocktail over the full mass range and in every p_T bins, except for some small deviations in the higher p_T bin (see discussion of high p_T below). In contrast, the low-mass enhancement in Au+Au is concentrated at low-p_T , as shown in Fig. 4. The p_T bin p_T <0.7 GeV/c is enhanced more than the inclusive data, the bin 0.7<p_T ¡1.5 GeV/c is enhanced less than the inclusive data, and in the last one p_T >1.5 GeV/c the Au+Au data almost agree with the p+p data.

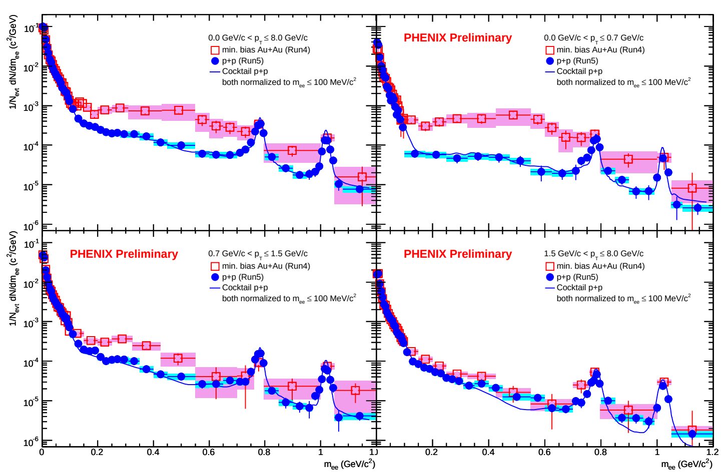

Figure 4. Invariant mass spectra of e^+e^- pairs in p+p and Au+Au collisions for different p_T bins.

Fig. 5 shows the transverse momentum spectra for different mass windows for Au+Au and p+p data and the expected contribution from hadronic cocktail and charmed mesons. In the low mass bins (up to 400 MeV/c^2) the yield is truncated at low pair-p_T due to the single-track p_T cut at 200 MeV/c. In contrast to the mass spectra, the p_T spectra are corrected for the acceptance, therefore represent the in-

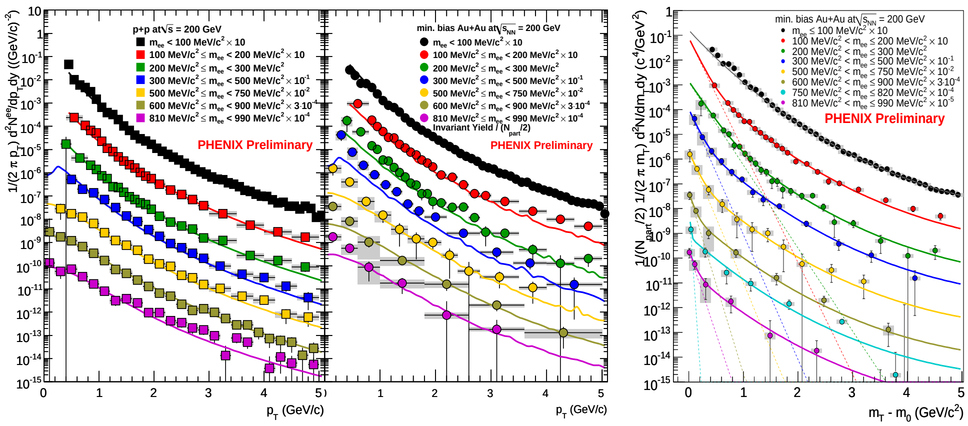

Figure 5. p_T spectra of e^+e^- pairs in p+p and Au+Au collisions for different p_T bins.

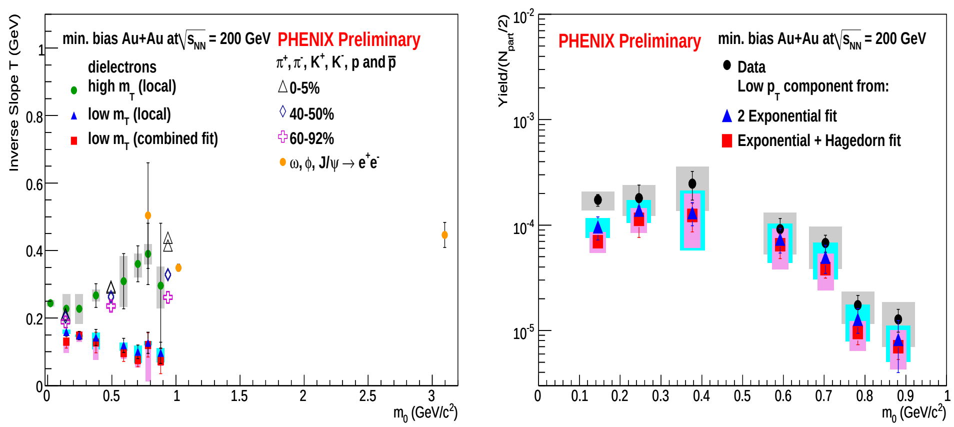

Figure 6. Left: Inverse slope T_{eff} of the e^+e^- pairs and identified hadrons. Right: e^+e^- pairs yield in different mass bins.

variant yield within $|\eta| \leq 0.5$ in pseudo-rapidity and $\phi = \pi/2$ in azimuth.

In the low-p_T region (p_T <1GeV/c) all the p+p spectra are consistent with the expectations from the cocktail. The Au+Au data agree with the cocktail only in the region $m < 100\text{MeV/c}^2$, while in all the higher mass bins the data show an excess that grows towards low-p_T despite the p_T > 200 MeV/c cut on the single electron track. The Au+Au spectra indicate a change of slope around 1 GeV/c. To extract information about the low-p_T component the Au+Au spectra was fitted with an exponential in m_T in two mass regions. The first fit is restricted to the low-p_T region (p_T <1GeV/c) and the second to a region where the data seem to follow the trend of the cocktail (1<p_T <2GeV/c). To account for the contribution of the cocktail below the low-p_T component, the spectra were fitted with the sum of two exponentials; alternatively a modified Hagedorn function was fitted to the mass range m_{ee} <0.1GeV/c^2 and then m_T -scaled to larger masses. The extracted values of T_{eff} are shown in

Fig. 6 (left) as a function of mass, together with the slopes of identified hadrons measured by PHENIX [30]. The hadron slopes rise linearly with mass, consistent with the expectations from radial expansion of the hadronic source. The slope of the e^+e^- pair spectra in the range $1 < p_T < 2$GeV/c, where the data are in reasonable agreement with the cocktail, seems to follow this trend. In contrast, the slope of the low-p_T component remains approximately constant at ≈ 120 MeV and does not show the rise with mass typical for a radially expanding source. Fig. 6 (right) shows the e^+e^- yield in each mass range obtained by integrating the p_T spectra. The panel also shows the yield of the low-p_T exponential extracted from the two fits described above (2 exponentials or exponential + m_T -scaled Hagedorn function). In either case the yield of the low-p_T exponential contributes at least 50% of the yield of the spectra.

While most of the e^+e^- yield pair enhancement in Au+Au is concentrated p_T $<$1GeV/c, some enhancement is also observed at higher p_T . PHENIX has also analyzed this in the p_T region $1 < p_T < 5$ GeV/c by comparing the spectra in p+p and Au+Au collisions to the expectations from the cocktail, as shown in Fig.7. The p+p

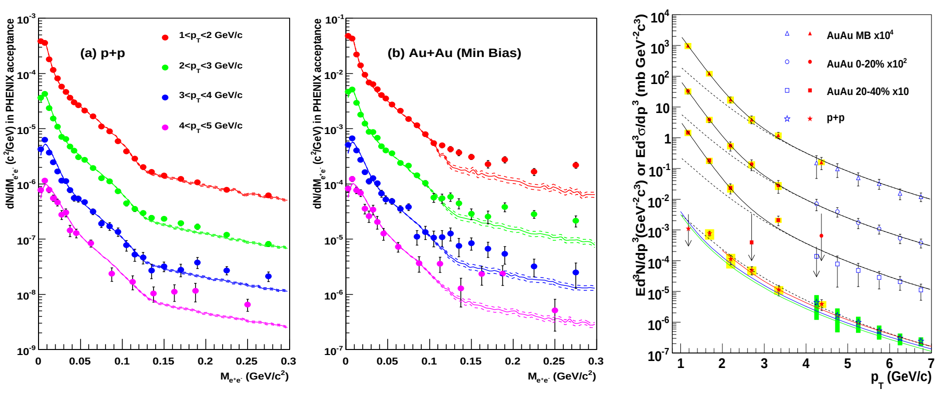

Figure 7. Left: The e^+e^- invariant mass distributions in (a) p+p and (b) minimum bias Au+Au collisions compared to a cocktail of hadronic sources. Right: Invariant cross section (p+p) and invariant yield (Au+Au) of direct photons compared to a NLO pQCD calculation (red, green, blue curve). The black curves are exponential plus modified power-law fit [29].

data are consistent with the cocktail with only a small excess in the higher p_T bins, while Au+Au data show a much greater excess. In the mass region $m_{ee} < 300\text{MeV/c}^2$ little or no contribution is expected from conventional sources since $\pi^+\pi^- \rightarrow e^+e^-$ can only contribute for $M_{ee} \geq 2M_\pi$. Since any source of real photons can also emit virtual photons which convert to low mass e^+e^- pairs, the excess was analyzed under the assumption that it is entirely due to internal conversion of direct photons which result in a mass distribution following the description by Kroll and Wada [31]. A two-component fit which uses the relative fraction of direct photons as only free parameter, allows to determine the fraction of direct photon component, consistent with the expectations from NLO pQCD [32] in p+p, but larger than the N_{coll}-scaled calculations in Au+Au. This is converted to the invariant cross-section/yield of direct photons, shown in Fig.7. The Au+Au data are fitted with an exponential plus a modified power-law function fixed to the p+p data and scaled by T_{AA}; the inverse slope $T = 221 \pm 23(\text{stat}) \pm 18(\text{sys})$ is related to the initial temperature T_{init} which, according to hydrodynamical models, is 1.5 to 3 times larger than T [33].

4. Conclusions

Measurements of Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV show an enhancement of the dielectron continuum in the mass range 150–750 MeV/c^2 in central collisions. The enhancement is absent in p+p and peripheral Au+Au collisions, where the observed yield agrees well with the calculated hadron decays contributions. The enhancement increases with centrality faster than proportional to N_{part}. Moreover the enhancement is concentrated at low-p_T with an inverse slope $T_{eff} \sim 120 MeV$ which does not exhibit a mass dependence and thus probably does not participate in radial collective flow. This low-p_T enhancement is qualitatively consistent with data from SPS experiments [6, 7]. None of the currently available theoretical models yet explains this low-p_T component. At $1 < p_T < 5$GeV/c the p+p data show a small excess over the hadronic background while the Au+Au data show a much larger excess. Treating the excess as internal conversion of direct photons, a direct photon yield is deduced. It is consistent with NLO pQCD calculations in p+p. In Au+Au it is consistent with hydrodynamical models with initial temperature $T_{init} \sim 300 - 600$ MeV at times of 0.6-0.15 fm/c.

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